Small Scale Propulsion

Fly on the Wall, Cockroach in the Corner, Rat in the Basement, Bird in the Sky

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This study concerns small vehicles on the battlefield, and in particular their propulsion. These vehicles may fly or travel on the ground by walking, rolling or hopping. Their purpose is to carry, generally covertly, a useful payload to a place inaccessible to man, or too dangerous for men, or in which a man or manned vehicle could not be covert.

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Contents

1 INTRODUCTION

This study[1] concerns small vehicles on the battlefield, and in particular their propulsion. These vehicles may fly or travel on the ground by walking, rolling or hopping. Their purpose is to carry, generally covertly, a useful payload to a place inaccessible to man, or too dangerous for men, or in which a man or manned vehicle could not be covert.

Small useful payloads usually are sensors, which may include visible or IR imagers, nonimaging photometers, detectors of lower frequency electromagnetic waves, detectors of various chemicals or ionizing radiation, seismic or acoustic sensors, meteorological instruments, *etc.*, together with means of storing or communicating the results of their measurements back to the user. Useful payloads may also include taggants to be released, or lethal or non-lethal weapons; the restriction to very small payloads may still permit the delivery of effective weapons if the accuracy of delivery is high (possible examples include explosives applied to locks and irritant gases released in confined spaces).

This field has been the subject of a great deal of speculation in the past. For example, many people have written about an artificial vehicle as small and inconspicuous as a fly or cockroach, which could fly or crawl into a denied area and transmit data. Unfortunately, an artificial fly or cockroach is far beyond present technology. It is possible to build vehicles as small as rats or small birds, but they are much less capable than the living organisms. There are several reasons for this: Fliers become more difficult to build and less efficient as their size decreases, partly for aerodynamic reasons (which also apply to living things) but also because motors and (especially) internal

[1] A small portion of this report was adapted from a 1993 JASON report "Fly on the Wall" by J. Goodman and J. Katz

combustion engines, unlike muscles, become less efficient at smaller sizes. Artificial crawlers and walkers are large, slow and poorly coordinated. They are far inferior to cockroaches or rats in speed and agility, and are larger than almost all insects. Similarly, artificial fliers are not nearly as agile as birds. Progress has been very slow. Land and air vehicles involve very different problems, and will be discussed in separate sections.

2 FLIERS

Fliers (such as the DARPA/TTO miniature air vehicle, or MAV) have two great strengths: they can fly over terrain obstacles, and they view the world from above. Their chief weakness is that their loiter time is limited, because they must expend a significant power to stay aloft. Flying animals solve this problem by soaring, by perching and by feeding in flight (or during short perches). This is not possible for machines: the analogous solar powered fliers and soarers can fly in only the most favorable (and infrequently found) conditions. As a result, the energetics of propulsion are central to the design and capabilities of MAV.

2.1 Model Aircraft

Hobbyists buy, build and fly radio-controlled model aircraft. One hobbyist has even mounted a commercial electronic camera on his model and has taken fine aerial reconnaissance photographs (see http://www.wco.com/ d̃greno/aboutsystem.html), although he did not transmit them to the ground by an RF link.

Have the hobbyists solved DARPA's problem? The answer is no, although they have done enough to be interesting, and a battlefield commander might find the hobbyists' systems useful if nothing better were available. There are four problems with the hobbyists' airplanes:

1. They are too big for easy battlefield transport. Most of them have wingspans of 3–5′, and the smallest commercially available flying model has a $19\frac{1}{2}''$ wingspan. If a reconnaissance system is to be made available to every

platoon a soldier must be able to carry it on his back along with his other gear. Weight is not the problem, but a large bulky object, enclosed in a rigid case because of its fragility, is an impediment even if its weight is negligible.

2. Most hobbyists' airplanes are powered by extremely noisy piston engines, which forfeit covertness, and which are notoriously temperamental. Anyone who has dealt with a gasoline lawn mower will recognize the problem, although model airplane engines use a different ignition system (a glow plug rather than a spark plug).

3. The endurance time and range of hobbyists' airplanes are inadequate. This is especially true of those powered by electric motors, which would otherwise offer the advantages of quiet operation and reliable starting simply by throwing a switch (ask anyone who owns an electric lawn mower).

4. Hobbyists sense the flight path and attitude of their models by looking at them. This only works as far as the eye can see (it must see the attitude of the aircraft), which would be roughly 100 m for a MAV. A MAV therefore needs either a capable programmed autopilot or real-time transmission of flight data (attitude and coordinates) to a controller.

Although the hobbyists have not solved DARPA's problem, they have accumulated a great deal of useful experience with small airplanes and their structures, propulsion and control. This should and can be drawn upon, and partially substitutes for an expensive development program. In particular, the fact that hobbyists have chosen to build airplanes with wingspans of several feet is a warning that at smaller sizes flight becomes more difficult. The reasons for this are discussed below.

2.2 The MAV Problem

1. Aerodynamics

The drag on a flying object may be written

$$F = \frac{gM}{L/D}, \tag{1}$$

where g is the acceleration of gravity, M is the object's mass, and L/D is its ratio of lift to drag. Ignoring the weak speed dependence of the dimensionless coefficient L/D, the range is

$$R = \frac{f_b \mathcal{E} \epsilon_e \epsilon_p L/D}{g}, \tag{2}$$

where f_b is the fraction of the mass which is fuel or battery, $\mathcal{E}$ is the energy stored per unit mass, ϵ_e is the engine efficiency and ϵ_p is the propeller efficiency.

At high speeds the drag increases. The characteristic speed may be obtained by writing

$$F = \frac{1}{2}\rho_a A v^2 C_D, \tag{3}$$

where ρ_a is the air density, A the vehicle's projected area in the direction of flight, v its air speed and C_D its drag coefficient. As speed increases the angle of attack (in level flight) decreases, and so do A and C_D. Above a characteristic speed v_{char} C_D and A are set by the fuselage and the wing camber, and cannot decrease further. This speed is now found by equating (1) and (3):

$$v_{char} = \left(\frac{2gM}{\rho_a A C_D L/D}\right)^{1/2}. \tag{4}$$

This is the speed at which the parasitic drag is comparable to the induced drag attributable to the wing's lift; the range decreases $\propto v^2$ at higher speeds.

For $M = 0.1$ gm, $A = 1$ cm^2, $L/D = 5$ and $C_D = 0.3$ we find $v_{char} \approx 3$ m/sec. Most engineering optimization processes will lead to speeds comparable to v_{char} or a little slower; it is not surprising that evolution has produced a similar optimization and that this speed is typical of flying insects. Slow speeds are undesirable for practical systems, partly because their mission may be urgent, but more importantly because unfavorable winds may keep them from ever reaching their destination. Therefore, fliers will generally be comparatively large and heavy, more comparable to small birds than to insects (even were it possible to build insect-sized fliers).[2] As will be discussed below, both propulsion and aerodynamics become inefficient for very small artificial fliers, quite apart from the disadvantage of their low v_{char} (insects and hummingbirds suffer from aerodynamic inefficiency, which requires them to have enormous appetites in proportion to their masses, even though they retain the efficient muscular metabolism of larger animals).

If M is increased to 50 gm and the product AC_D increased to 3 cm^2, then $v_{char} \approx 23$ m/sec, sufficient to overcome most winds likely to be encountered. Such comparatively large fliers are easier to build than very small ones, but are still small enough to make covertness possible. They may be built with small propellers (impossible in macroscopic animals because of the difficulty of carrying fluids across rotating joints) and conventional aircraft control surfaces, rather than flapping wings; they will resemble microscale helicopters or airplanes rather than living birds. Propeller tip speeds for efficient operation are $O(v/\theta)$, where θ is the blade pitch; because this may be small the acoustic emission and signature need not be large.

The preceding scaling laws seem to imply that, so long as v is not too large, the range should be independent of vehicle size (and that the endurance

[2]Most of the few insects which fly long distances by their own directed efforts (rather than being passively carried by the wind), such as locusts, are comparatively large and heavy. Monarch butterflies, which migrate, are very light, their flight is slow and low, and they are very vulnerable to adverse winds.

time might even be larger for smaller vehicles, because they can fly more slowly). Unfortunately, this is not the case. The single most important parameter describing an airplane is L/D. Because of the lower Reynolds numbers ($\sim 10^4$–10^5) and wing aspect ratio L/D is smaller for small airplanes than for large ones. Values in the range 3–8 are estimated for MAV, in contrast to 15 for commercial jets and up to 60 for the best sailplanes. We will usually adopt $L/D = 5$, which is probably realistic.

$\mathcal{E}$, ϵ_e and ϵ_p are smaller at small scales because of quantities (manufacturing tolerances, heat loss to walls, resistive heating *etc.*) which do not scale with size and because of a reduced Reynolds number within an internal combustion engine.

In addition, the lower speed of small airplanes (v_{char} scales as the 1/2 power of the linear dimension, if components remain geometrically similar) makes them more vulnerable to unfavorable winds. If a small flier is designed for the same speed as a larger one it will generally have short stubby heavily loaded wings and a low L/D. A 6″ 50 gm MAV has a high wing loading and small aspect ratio (compared to extrapolations from model airplanes), and AeroVironment has reported L/D as low as 3.

2. Propulsion Options

The critical parameter in propulsion is the specific energy stored $\mathcal{E}$. Four kinds of propulsion may be considered: battery-electric, fuel cell-electric, piston engine and gas turbine. In birds and insects muscular propulsion scales very well to small sizes. Unfortunately, this is not true for most artificial means of propulsion, and the size dependence of $\mathcal{E}$, ϵ_e and ϵ_p is important.

a. Batteries

The value of $\mathcal{E}$ for $LiSOCl_2$ (lithium thionyl chloride) primary batteries

is estimated in standard handbooks to exceed 400 Wh/kg and at least one manufacturer talks of 700 Wh/kg. However, the maximum deliverable power (or current) is also limited by internal resistance, and attempts to draw high power from a battery reduce the total energy which can be drawn. The relevant parameter is the draw-down time, which for MAV is about an hour.

Engineering the batteries to provide the required high power and short draw-down time is not trivial, and implies a significantly smaller value of $\mathcal{E}$ because most lithium batteries have been designed for low power applications. In order to obtain a realistic estimate of performance we called a major manufacturer, the Eagle-Picher Corp.[3] We were told that a customized 28 gm two cell battery could provide 1.5 A at a nominal 6 V for one hour. This corresponds to 320 Wh/kg in a package suitable for powering a MAV of about 100 gm. We will henceforth take $\mathcal{E} = 300$ Wh/kg $= 1.08 \times 10^{10}$ erg/gm for batteries.

b. Fuel Cells

Fuel cells may provide values of $\mathcal{E}$ as large as 1200–3000 Wh/kg. This may be extremely attractive, but it is unclear what power they can provide. As for batteries, the value of $\mathcal{E}$ is intrinsically independent of size. Fuel cells are a technology with a long history of promise, but which has proven to be practical in comparatively few cases, chiefly because of the difficulty of finding suitable catalysts.

c. Piston Engines

Internal combustion engines appear to offer the advantage of the very high heat of combustion of their fuels. For hydrocarbons $\mathcal{E}$ is typically about 13 Kcal/gm $\approx 5 \times 10^{11}$ erg/gm, roughly 50 times greater than the value we have assumed achievable for batteries. Model airplane fuel is typically a

[3]Mark Peabody at 417-623-8000 X330

mixture of methanol (65%), nitromethane (15%) and castor oil (20%) (these percentages are those recommended by Cox for its very small engines), giving $\mathcal{E} \approx 1.3 \times 10^{11}$ erg/gm, only 12 times our value for batteries.

The efficiency of the tiny engines used in model airplanes is very small. The smallest mass-produced engine is the Cox TD 010 Model 130 of .010 in^3 displacement. Operating at 30,000 rpm it consumes 0.052 oz/min of fuel[4] (approximately three times more than the flow stoichiometrically corresponding to the displacement volume and cycle rate). This fuel flow gives an equivalent thermal power of 250 W, although the majority of the fuel does not appear to be burned. The useful work done may be roughly be estimated by noting that this engine is recommended (Tower Hobbies catalogue) to power a 165 gm airplane. Assuming $L/D = 8$, a 50% propeller efficiency and an airspeed of 16 m/s (typical for model airplanes) yields a required propulsive power of 3.2 W, shaft power of 6.5 W and fuel-to-shaft power efficiency $\epsilon_e = 2.6\%$. The actual efficiency, power and level flight speed may be higher than these estimates (Lincoln Labs estimates the shaft power as 20 W and the efficiency as 5.5%, using a larger value for the fuel consumption), but these uncertainties do not reduce the equivalent thermal power and fuel consumption. These tiny engines are unmuffled and extremely loud; addition of a muffler, if possible at all, would probably exact a substantial additional penalty in efficiency.

A MAV would require a yet smaller engine (with plausible values of $M = 50$ gm, $L/D = 5$ and $v = 15$ m/s the shaft power becomes 2.9 W, about half as large as estimated for the model). Lincoln Labs is developing a 0.003 in^3 piston engine, but such an engine is likely to be even less efficient. These low efficiencies remove the only apparent advantage of internal combustion engines over batteries, the high specific energy of chemical fuels.

[4]Data from manufacturer by telephone inquiry to 800-525-7561.

d. Electric Motors

The efficiency of small electric motors is much larger. We do not have many data, but AeroVironment quotes for its 40 gm MAV a 35% motor efficiency (compare to efficiencies > 80% at horsepower sizes). This is 13 times better than that of the Cox TD 010 and compensates for the higher energy density of internal combustion fuels. This comparison is in fact unfair to the electric motor, which is much lower power than the internal combustion engine to which it is being compared (the electric motor powers a 40 gm MAV with 6″ wingspan while the TD 010 powers a 165 gm model with $19\frac{1}{2}''$ wingspan). An electric motor sized to the model would be more efficient, and an internal combustion engine sized to the MAV would be less efficient.

e. Gas Turbines

There is an effort at the MIT Gas Turbine Laboratory under the leadership of A. Epstein to build a micromachined gas turbine of 4 mm diameter. This is predicted to convert combustion energy into mechanical energy with an efficiency up to 30%, and will be a remarkable accomplishment if successful. Initial versions will consume H_2 fuel, probably impractical for a MAV because of the need for a comparatively massive pressure vessel to contain it (a Kevlar reinforced composite pressure vessel stressed to 4 Kbar is 6.5 times the mass of the room temperature hydrogen it contains) or cryogenic liquid H_2, but later versions are expected to consume hydrocarbons. The baseline design consumes 7 gm/hr of H_2, which corresponds to a gross thermal power of 276 W. This is predicted to produce 16 W of electric power (at 3–5 MHz AC and 400 V, which will require conditioning before it can be used in a motor). The thermodynamic efficiency is then about 6%, far below the efficiencies of "full size" turbines, which approach 50%. If this turbine could be operated with hydrocarbon fuel the 6% thermodynamic efficiency would

reduce the electric energy produced per unit mass to about twice the value obtainable from batteries.

The MIT team has also designed a recuperative microturbine burning hydrocarbons, which they predict will have a thermodynamic efficiency of 30%. This is a more difficult goal, in part because of the increased complexity of fabrication with a recuperator, and in part because at small scales combustion of hydrocarbon becomes more difficult as the chemical reaction time (~ 0.1 ms) begins to approach the flow time through the reaction chamber (this difficulty does not arise in burning hydrogen, whose reaction with oxygen is an extremely simple and rapidly branching chain).

We have so far assumed that the turbine is used to make electricity to drive an electric motor. It is also possible to consider turbojet and turbofan propulsion, but these are very inefficient at MAV speeds. A turboprop engine would require reduction gearing to drive an appropriately large and slow propeller, and power-handling gears may be difficult to build at the necessary scale and stress levels (recall that the turbine tip speed is limited only by materials strength; the driving gears must therefore be smaller than the turbine and there will be large contact stresses in brittle materials).

3. Propulsion Scaling

Table 1 summarizes the preceding efficiency estimates. Table 2 presents estimates of the fuel (or battery) mass required to fly a 50 gm MAV with $L/D = 5$ and propeller efficiency $\epsilon_p = 0.5$ at $v = 15$ m/sec for one hour. Piston engines are unattractive, while either the $LiSOCl_2$ battery electric motor or the hydrocarbon microturbine appear satisfactory. The battery and electric motor are the demonstrated state of the art. The hydrocarbon powered microturbine represents a substantial step beyond the hydrogen powered microturbine now under development.

Table 1.

	$LiSOCl_2$ electric	Cox TD 010 piston	hydrocarbon microturbine	H_2 microturbine
$\mathcal{E}\epsilon_e$ (erg/gm)	3.8×10^9	3.4×10^9	9.4×10^9	2.7×10^9

For electric motors $\epsilon_e = 0.35$. For TD 010 $\epsilon_e = 2.6\%$; the Lincoln Lab. estimate is twice as large. For the microturbine ϵ_e is the product of the estimated efficiency of electric power generation with H_2 fuel, $\mathcal{E}$ appropriate to the fuel actually used, and an assumed $\epsilon_e = 0.35$ and 80% power conditioning efficiency. For H_2 fuel a Kevlar reinforced composite pressure vessel at 4 Kbar is included in the mass.

Table 2.

	$LiSOCl_2$ electric	Cox TD 010 piston	.003 in^3 piston	hydrocarbon microturbine	H_2 microturbine
Fuel Mass	28 gm	69 gm	31 gm	15 gm	53 gm

Fuel or battery mass required for 1 hour flight of a 50 gm MAV with $L/D = 5$, $v = 15$ m/sec, $\epsilon_p = 0.5$. The .003 in^3 piston engine is assumed to have 0.45 the fuel consumption of the Cox TD 010, but the same efficiency (this assumes a revolution rate proportional to the -1/3 power of the displacement, as found for larger model airplane engines). The hydrocarbon microturbine is assumed to burn n-octane at the same thermal power as the baseline consumption of H_2. The H_2 microturbine includes the mass of a Kevlar reinforced pressure vessel confining H_2 gas at 4 Kbar. *N.B.*: The TD 010 and the microturbines are overpowered for the MAV, and their fuel consumption is set by their size, not by the required shaft power.

If we assume $L/D = 5$, $\mathcal{E} = 300$ Wh/kg, $f_b = 0.5$, $\epsilon_e = 0.5$ and $\epsilon_p = 0.5$ (the last two numbers assume some improvement over the AeroVironment MAV) then the flight range $R = 69$ km, large enough for many missions. At a speed of 10 m/sec the time airborne is nearly two hours. We note that this is several times longer than the flight times of 6–8 minutes typical of hobbyists' models. The chief reason for this is that hobbyists use NiCd batteries, a mature consumer technology which provides high specific power but a specific energy of only 40 Wh/kg, eight times less than provided by $LiSOCl_2$.

These numbers illustrate the difficulties of propulsion scaling to small sizes. The baseline H_2 turbine is very inefficient, yet at 16 W electric output it

produces more power than a 50 gm MAV needs (roughly 1 W aerodynamic power and perhaps 5 W electric power for cruise, and up to twice these values for climb and maneuver). The more elaborate recuperative turbine is expected to have a quite respectable thermodynamic efficiency, but there is no use for the extra power. We conclude that the proposed microturbines are in fact too *large* and powerful for the contemplated MAV; however efficient they may be, they burn so much fuel that the required mass is comparable to that of a properly sized battery.

It is unclear whether a significantly smaller turbine could be built. At scales below the proposed 4 mm diameter a number of physical processes (viscosity, conduction to the walls, time available for combustion, *etc.*) scale unfavorably. Below a certain (presently unknown) size scale a turbine does not produce enough power to drive its compressor stage, and fails entirely.

The efficiency of piston engines also decreases as their size shrinks. The values of a few percent estimated for the TD 010 are nearly tenfold smaller than the values of about 25% found for automobile engines. In addition, in order to be ignited model airplane fuel consists of methanol and nitromethane (in pure form, a high explosive) which have much lower heats of combustion than hydrocarbons. It also contains a significant quantity of nonvolatile lubricant which does not burn. Small size imposes other inefficiencies: primitive valving, excessively (for efficiency) rich fuel/air ratios, proportionately poorer piston/cylinder fit, greater conductive heat loss, *etc.* These inefficiencies are likely to get worse at smaller sizes, although they could be improved by development and manufacturing efforts beyond the resources available to the companies which supply the price-sensitive hobbyist market.

Batteries scale much more favorably than internal combustion engines. In principle, their specific energy storage and specific power should be scale-invariant. This is not usually true of commercial batteries, probably because

the same gauge casing is used for small batteries as for large ones, but this can readily be remedied. The specific energy we have assumed ($\mathcal{E}$ = ∋// Wh/kg) is appropriately sized to a MAV.

The efficiency of electric motors decreases as they become smaller, but the decrease is not as dramatic as for internal combustion engines. For a permanent magnet motor the power density is $\vec{v} \cdot (\vec{j} \times \vec{B})$, where $\vec{v}$ is the rotor velocity and $\vec{j}$ the current density, while the resistive loss power density is j^2/σ, where σ is the conductivity. Both these power densities and their ratio are size-invariant if $\vec{j}$ and $\vec{v}$ are size-invariant; the rotation rate must then be inversely proportional to the size. However, this leads to a torque/power ratio which is proportional to size, and is small for small motors. To obtain higher torque the rotation rate must be reduced, but then keeping the power density constant requires increasing $\vec{j}$, reducing the efficiency. The efficiency of small motors also suffers for other reasons, such as the absence of ball bearings, the failure of lubricant properties to scale, proportionately poorer tolerances and the fact that at constant power density the smaller rotor rotates more times in its energy flow time.

For example, 1 hp motors are typically $> 80\%$ efficient, but AeroVironment estimates that the micro-scale motor used in their 40 gm MAV has an efficiency of 35%. It may be possible to design micro-scale motors with higher efficiency, and 50% is considered plausible.[5] Small electric motors of high power density generally use samarium-cobalt permanent magnets, and the development of this material was an essential step in making electric-powered MAV (and hobbyists' models) practical.

Propeller efficiencies also decrease as sizes become smaller because of the decline in Reynolds number. This is a burden which all propulsion mechanisms must bear. AeroVironment estimates a 40% propeller efficiency in

[5] Jeff Lang, Electrical Engineering MIT 617-253-4687.

their MAV, but it is possible that this may be improved by custom design.

2.3 Has the MAV Problem Been Solved?

AeroVironment[6] has built and flown a $1\frac{1}{2}$ ounce (40 gm) electric MAV, fitting within the DARPA 6″ limit, which carries a 300 × 240 pixel camera. Although they were unwilling to disclose full performance figures and engineering details, they estimated $L/D = 3$, $\epsilon_e = 0.35$ and $\epsilon_p = 0.4$. The remarkably low L/D is a consequence of its short stubby wings, and a substantially greater L/D could be obtained if the restriction of wingspan to 6″ were relaxed. The camera, although not state of the art, certainly has enough resolution to be useful.

This is an existence proof of the feasibility of MAV within the DARPA size constraint. It is not yet a functioning prototype of a useful system: it does not have the required navigation and flight control system (it is flown like a model, by visual observation of its position and attitude), but its builders are proposing to develop suitable avionics and data telemetry link. It does establish that the basic problem of airframe, propulsion and imaging sensor is solvable.

[6] Matt Keennon and Ray Morgan 805-581-2187.

3 ROBOTIC LAND VEHICLES

Travel across land is beset by obstacles: terrain, vegetation, water and artificial barriers. Because of these obstacles long distance cross-country travel by a small machine is unlikely to be possible. Living animals are capable of overcoming most natural barriers, but robotic land vehicles are much not. For example, we suggest the hedge test: A cockroach, rat, dog, man and horse find no difficulty in crossing a 1′ hedge, but it will stop all small robotic vehicles we know of.

For this reason, robotic land vehicles are unlikely to be used to travel long distances off roads.[7] Instead, they may be used to carry useful payloads small distances into denied areas, such as the interiors of structures, perhaps after being delivered by air (necessarily by a larger vehicle than the MAV discussed in earlier sections). In short distance travel energetic bounds on range are much less important than the ability to overcome obstacles and remain covert.

Several types of land locomotion may be considered. Most animals walk on four, six, eight or more legs with a variety of gaits, and numerous robots have been constructed on similar principles. Some animals hop (kangaroos, grasshoppers, fleas, *etc.*), and it is possible to consider hopping robots. Legless land animals (snakes, worms, insect larvae, legless lizards *etc.*) move with surprising agility (some snakes are good tree-climbers and feed on bird eggs) and speed by a variety of mechanisms; except for inchworm propulsion these appear not be used in robotic vehicles. Wheels are the mainstay of vehicular propulsion, but continuous rotary motion is not found in nature above the cellular scale. "Caterpillar" treads and tracks (which are not used

[7]There may be a niche for wheeled vehicles traveling on roads, either at small scale or in the guise of ordinary automobiles.

by caterpillars) are used in vehicles designed for rough terrain. There is a related toy of toroidal topology (a rubberized water-filled cloth bag) which can creep by being turned inside out; this may be the best way to build a crawler for the inside of ducts and pipes.

The following section briefly considers the applicability of some of these methods to robotic vehicles. The issue of interest is not energetics but agility. Living organisms do an excellent job of integrating their sensory and actuating systems (eyes, nerves and muscles). For example, an animal sees obstacles ahead and smoothly adjusts its gait to avoid or surmount them. This is an unsolved problem for robotic vehicles, which is one of the chief reasons they are so slow—each leg must sense and adapt its motion to the terrain and obstacles, one step at a time. In addition, just as for flight, muscles and nerves scale very well to microscopic sizes (with little loss of efficiency or control), but artificial actuators do not.

3.1 Hoppers

Some insects (and larger animals) travel by hopping. For ballistic hops the maximum range, assuming landing to be competely inelastic, is

$$R = \frac{2 f_b \mathcal{E} \epsilon_h}{g(1-\eta)}, \tag{5}$$

where ϵ_h is the thermodynamic efficiency of the heat engine which drives the hops and η is the fractional energy recovery after a hop. The range is several times smaller than for fliers. It can be increased by a factor of approximately L/D to the value for fliers given by Equation (2) if the hopper deploys wings and glides downward. The ratio of air drag to weight of a hopper is $Av^2C_D/(2gM)$, which requires hoppers which must travel kilometers to be comparatively massive, just as fliers must be.

Hoppers occupy an intermediate ground between fliers and walkers, depending on the length of their hops. For very long steps they amount to short range gliders, while for small steps they resemble walkers.

A possible hopper consists of two cylinders of slightly different diameter, the smaller sliding inside the larger, and each closed at one end and open at the other so as to form a closed interior volume. There must be a stop ring so that the cylinders cannot separate completely, and shock absorbers at both ends of their relative travel. On the outside of one of the cylinders is a heavy and broad tripod base which will hold the hopper upright when it lands; the weight of the base insures that it lands pointing downward. Rapid combustion of fuel inside the cylinders accelerates the upper cylinder upward, and the stop ring ensures that the lower will follow. This minimal design requires, however, more elaborate aerodynamic controls in order that the hopper go where it is needed. A battery-powered hopper would have a spring in place of the fuel, and would require a motor and mechanism to compress the spring.

Obstacles are a severe problem for hoppers. A landing on rough or vegetated terrain may upset the vehicle, or it may become entangled in or trapped below vegetation. Hopping animals manage the problem with sophisticated integration of their sensory, nervous and muscular systems which is far beyond the present state of the art in robotics. Long distance hopping is useful for kangaroos which live in open terrain, but most other animals which hop or jump do so occasionally to launch a run or flight or to overcome an obstacle, rather than as a means of long distance travel. Hopping is also attractive for very small animals such as fleas, for which a walking gait would be very slow and incapable of bridging gaps (between two host animals, in the case of the flea); the speed, and therefore length, of a hop are nearly independent of of the size of the hopper.

3.2 Crawlers and Walkers

Crawling and walking robots, like crawling insects, are permitted by the laws of physics to be very small, although it is not known how to build them at sub-cm sizes. Their range is determined by an effective coefficient of friction C_f, reflecting losses in flexing joints, bearings, contacts with the ground, *etc.*, and is

$$R = \frac{f_b \mathcal{E}}{g C_f}. \tag{6}$$

This range may be very large (530 km for $C_f = 0.1$, $f_b = 0.5$ and $\mathcal{E} = 300$ Wh/kg), and it has no explicit size dependence.

Man-made crawlers are generally slow, with speeds measured in meters per minute rather than meters per second. The example of ants demonstrates that natural crawlers can overcome any fixed barrier (but not flowing water), but man-made crawlers are not nearly so capable. In order to replicate this ability, crawling robots will need great agility on rough terrain, algorithms capable of keeping them on course in the presence of obstacles, and sticky feet to enable them to climb. These are beyond the state of the art.

Present robot builders are working on the problems of agility and algorithms, but with much larger robots and with modest budgets; extant robots are much too large and clumsy for our purposes. It may be necessary to climb walls; for this sticky feet or suction cups which remain effective after walking on a variety of rough, dirty, and dusty surfaces are necessary. Small lizards and insects use conformable suction cups, pinned three-phase contact lines or tacky glue, presumably discarded and replenished as they become ineffective; research will be required to adapt these methods to artificial systems.

4 COMMUNICATIONS AND DATA LINKS

A flying electric 50 gm MAV spends several Watts on propulsion. It is therefore reasonable to assume 1 W available for data transmission. Suppose it is desired to transmit a 2 Megabit image (250,000 pixels @ 8 bits) every 3 seconds, which corresponds to a series of adjacent 500×500 pixel images with 10 cm resolution (50 m $\times$ 50 m) forming a continuous track under a MAV flying at 15 m/s. Assuming isotropic emission and a clear line of sight to a 100 cm^2 antenna and a receiver with 300°K noise temperature, this power provides 10 dB signal/noise out to 100 km range.

We now consider a long endurance sensor delivered to a remote location, for which the available power is much less. Because crawlers are slow, but can be inconspicuous if they can be miniaturized sufficiently (the artificial cockroach), and may be capable of traversing almost any obstacle and passing through small apertures (under doors, *etc.*), a multi-stage delivery system is conceivable. A comparatively large and high-signature RPV would deliver a 50 gm flier to within 50 km of a target. The flier would fly to within perhaps 100 m of the target, and there drop or land with a number of 0.1 gm crawlers. The tiny and low-signature crawlers would carry sensors and transmitters to points of interest—inside rooms, on roofs, inside vents and exhaust stacks, *etc.* The flier could land and remain, to serve as a repeater for low power transmissions of the crawlers. An orbiting or visiting RPV could, if necessary, serve as an information collector or a higher power repeater for signals from the flier. This three-stage system would take advantage of the fact that small objects of low signature (resembling the proverbial fly on the wall, or the familiar cockroach in the corner) can be hidden in a small area which is regularly visited or inspected, but larger objects with greater signatures may survive in a larger region subject to less careful inspection.

A 0.1 gm crawler with $f_b = 0.5$ and a 1 year endurance has available 0.34 μW of mean power for sensing, processing, housekeeping and communication (assuming 80% of the battery's energy has been spent on locomotion). For a 50 gm flier the corresponding power is 170 μW. These power budgets point toward a multi-stage repeater system for communication. If 50% of its power is devoted to communication then the crawler can transmit a steady 3×10^4 bits/sec at a signal-to-noise ratio of 10 db to a 10 cm^2 cross-section antenna at 100 m range (assuming no attenuation and a receiver noise temperature of 300°K), and the grounded flier (requiring 1 year endurance) can similarly transmit the same bit rate to 2 km range, or to a 100 cm^2 antenna at 6 km range. This is sufficient to monitor continuously an acoustic, geophonic or other low data rate sensor. A 250,000 pixel image could be transmitted in about a minute, and a variety of methods (data compression, change detection, store and forward, *etc.*) are available to obtain images of faster events while keeping the mean data transmission rate down.

Actually constructing useful crawlers, especially in the tiny sizes required to slip under doors and remain inconspicuous, is much more difficult than demonstrating theoretical feasibility. This is illustrated by the limited capabilities and large size of present autonomous vehicles. There are two quite difficult classes of unsolved problems: the engineering of insect-sized crawlers and bird-sized fliers, and the problem of autonomous operation. Major advances in micro- and nano-fabrication offer hope for rapid progress in the first problem, while the latter problem is old and progress is likely to be slower.

5 CONCLUSIONS

1. The MAV program is ambitious but is probably feasible. If it turns out to be too difficult, relaxing the size constraint (for example, to 12″) will make it much easier.

2. Useful crawlers or walkers are much more difficult, and will require an effort sustained over many years. DARPA should think in terms of 10–20 years, rather than 3–5 years. The limited progress made in the four years since we first examined this problem emphasizes the need for long-term efforts.

3. The really hard problems are those which require sensory integration or "artificial intelligence". These have defeated the best efforts of several decades and success is unlikely. There is a fair prospect of building crawlers and fliers which operate under external direction or according to fixed instructions. Attempts to build useful and truly autonomous systems are likely to fail, as are attempts to build crawlers and walkers approximating the performance of living cockroaches or rats.

A great deal of relevant expertise resides among biomechanicians concerned with insect and bird flight and locomotion. They should be full participants in this effort, along with micro- and nano-machine builders. Nature has found solutions to many of the problems faced by robotic crawlers and fliers, and advantage should be taken of this.

A APPENDIX: Remotely Piloted Animals

Living animals run on four or six legs much faster and with greater agility than robots and negotiate difficult terrain well. They achieve an integration between their sensory and nervous systems and their musculature, including the ability to use the data obtained by looking ahead, which has so far eluded the builders of robots. We therefore suggest remotely piloted animals may be useful.

Researchers at Tsuka University implanted electrodes and a microprocessor in a cockroach, but the resulting "RoboRoach" is much bigger and more conspicuous (as well as probably less agile) than a natural cockroach. It cannot fit through small cracks and crevices. It is unclear how well the roach responds to signals from the electrodes, and to what extent the implant may be miniaturized.

For most tasks on land we suggest rats, which are intelligent, cheap and readily available. We assume the rat can be trained (avoiding the expense of surgical implantation of electrodes) to respond to designated stimuli—electric or acoustic—by turning left or right, proceeding forward or stopping. Even a horse (a remarkably stupid animal) can do as much. The rat would be equipped with a small video camera, a transmitter, a device for supplying the stimuli, a battery and perhaps other sensors or useful devices. If this equipment hangs from a collar it would be inconspicuous, and would not greatly interfere with the rat's ability to squeeze through narrow apertures. The rat is then directed to the site of interest by signals from a remote human operator, who monitors its progress from transmitted images. Rats are small enough to pass through most fences, and even enter buildings through sewer pipes, emerging in toilets. They are big enough (a mature common rat weighs more than a pound) to carry several ounces of useful payload. Rats

are familiar and unavoidable (if unloved) inhabitants of most landscapes and especially battlefields, and their speed and agility make them difficult to observe or trap. During training the rat should not become habituated to people, so that it retains the natural wariness of a wild rat.[8]

[8]To make a canine analogy, we don't want the rat to approach every person it sees with tail wagging, in hope of a head-scratch and something to eat.

B APPENDIX: Microrockets

Small liquid-fuel rocket engines can probably be fabricated by MEMS techniques, but their utility is less clear than that of small turbines. They face strong competition from small solid-fuel rockets (for one-shot use) and from small monopropellant or bipropellant thrusters manufactured by standard techniques.

Space launch from the ground of small payloads (1–10 kg) by small launch vehicles (30–300 kg) does not seem promising because atmospheric drag scales unfavorably with vehicle size. The atmosphere presents a mass column density of $\sim 1000\ \mathrm{gm/cm^2}$ to any launch vehicle, which must pierce it with its own mass column density of

$$M/A \sim \rho\ell = 100\,\mathrm{gm/cm^2}\left(\frac{\rho}{1\,\mathrm{gm/cm^3}}\right)\left(\frac{\ell}{100\,\mathrm{cm}}\right), \qquad (B1)$$

where m is the launch vehicle mass, A its cross sectional area, ρ its mean mass density, and ℓ is its length. Streamlining helps, of course, but the fundamental fact is that M/A scales with the first power of ℓ, so small launch vehicles are strongly disfavored. Historically, small launch vehicles such as Scout, Vanguard, and Jupiter C have been much skinnier than large vehicles such as Saturn V and Energia; this is why.

Small launch vehicles could be efficient if launched from from high-altitude aircraft or balloons above most of the atmosphere. At an altitude of 60,000 feet the launcher would be above $\sim 90\%$ of the atmosphere, and a rocket 1/10 the length (and 1/1000 the mass) of one launched from sea level would make sense. This is the reason Pegasus is carried aloft by an airplane to about 40,000 feet before its engine is ignited.

C APPENDIX: Why mortars?

The Program Information Pamplet Attachment II to DARPA/TTO BAA 97-29 and 97-30 (Micro Air Vehicles, henceforth MAV) considers MAV launched by a 120 mm mortar. We do not believe this is necessary or desirable. Launch by mortar imposes two penalties: the requirement for a bulky and heavy mortar tube and shell, and a 16,000 g launch load on the vehicle. Most design concepts for MAV are light fragile structures, unlikely to survive a 16,000 g launch load, and a structure sturdy enough to survive launch by mortar would probably be too heavy to fly. Aircraft are usually designed with limiting strength somewhat (but not a large factor) in excess of their maximum maneuver loads, which are generally less than 10 g.

Instead, we suggest JATO (jet-assisted take-off). The flight speed of a MAV is typically around 15 m/s, as is that of the smaller and lighter hobbyists' models, which have a similar wing loading, and the stall speed is unlikely to exceed 10 m/s. Launch along a 1 m rail to 10 m/s implies an acceleration of 5 g. If necessary, lower accelerations can be obtained with a longer rail. The required launch force for a 50 gm MAV is 2.5 N and the impulse is 0.5 N-s, delivered over a time 0.2 s. These are roughly the parameters of the smallest toy rocket engines, which can be bought at hobby shops and toy stores.

In fact, even JATO is not necessary for launch. Model sailplanes are often launched with a slingshot ("hi-start"). The stall speed and mass of a MAV are low enough that it might simply be thrown into the wind.

The mortar offers a "head start", delivering the MAV to a release point which may be several km from the launch point. However, this is probably not critical, because the flying range of a MAV may be of order 100 km). A

10 km head start then only increases the range by 10%, and reduces the time to target by 15 minutes.

An additional disadvantage of mortar launch is that it requires the MAV to fit within a mortar shell. This limits the wingspan to less than 120 mm. A somewhat larger MAV will be easier to engineer. By demanding less miniaturization the aerodynamic and engine efficiency will be greater, and the tolerances required (especially on engine parts) less stringent. In addition, relaxed dimensional constraints permit reduced wing loading, which would permit slower flight speeds and longer loiter times.

However carefully engineered the airframe, flight controls and propulsion, and however sophisticated the sensors and communications links, a MAV resembles a hobbyist's model. This should be a source of pride, rather than embarrassment, if it means that the best advantage has been taken of a cheap existing technology. One of the advantages of this technology is that small model airplanes are easy to launch.

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